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NASA/Navy Lift/Cruise Fan

Cost Reduction Studies

by

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16. Abstract

Cost reduction studies were performed for the LCF459 turbotip fan for application with the YJ97-GE-100 gas generator in a multimission V/STOL research and technology aircraft. Primary objectives of the design studies were to achieve a 20 percent cost reduction of the research configuration based on the original preliminary design. This report covers the trade studies performed and the results in the area of cost reduction and weight. A fan configuration is defined for continuation of the program through the detailed design phase.

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1.0 INTRODUCTION

The General Electric Company, in a joint effort with NASA, has been engaged in a continuing program to define the advancements in component and system technology which will lead to advanced lift fan systems applicable to vertical and short takeoff and landing (V/STOL) aircraft. The turbotip lift fan concept has been shown consistently to be an attractive system for propulsion in V/STOL aircraft.

Recently, an application was identified using V/STOL aircraft to meet the Navy applications in the mid to late 1980 period. Integrated NASA sponsored aircraft and propulsion studies were conducted and succeeded in defining the specific requirements of the turbotip fan system for this Navy multimission aircraft. Subsequent preliminary design studies were completed and are summarized in Reference 1. The specific turbotip fan system selected was a 59-inch diameter fan driven by a growth version of the J97 engine. The propulsion system consists of three gas-coupled fan systems and either two or three engines. The fan system was identified as the LCF459.

In coincidence with these activities, NASA initiated studies to define a research and technology aircraft (RTA). The intent of this aircraft program is to provide a technology base directly applicable to the needs for the operational aircraft system. The aircraft is to be a modification of an existing aircraft which is in a gross weight category comparable with the operational aircraft. In addition, the propulsion system will be representative of the operational system, with design changes and modifications consistent with a low cost, low risk approach.

In support of this activity, design studies were conducted, under contract with NASA, to determine changes and modifications of the LCF459 for reductions of cost. The gas generator for use in the RTA Program was also defined as the YJ97-GE-100. This engine is a close derivative, with only minor changes, of the available YJ97-GE-3 engine used in a different aircraft program.

This report summarizes the results of these cost reduction studies directed towards definition of a turbotip fan system for the NASA research and technology aircraft.

2.0 SUMMARY

Preliminary design studies have defined the LCF459 turbotip fan for use as propulsion in a multimission Navy V/STOL aircraft. NASA is also considering a research and technology aircraft (RTA) using similar propulsion systems. A study was performed to define those design changes of the LCF459 that would meet the requirements of the RTA and at the same time show a reduction in manufacturing cost of the fan system. Design changes were defined which yielded 15 percent lower fan unit costs. These changes included the following:

- Substitution of lower cost materials whenever possible.
- Simplification of scroll geometry and mounting.
- Modified turbine-to-fan blade attachment including a new cooling system.
- A simplified integral bearing lubrication system.

The cost of incorporating these numerous features in the LCF459 fan produced a weight increase from 386 kg (850 lbs) to 416 kg (917 lbs). The design changes also represent additional benefits in lower risks and increased reliability over the original design.

3.0 REQUIREMENTS

3.1 Duty Cycle

The propulsion system for a research aircraft is required to operate in an environment quite different from the operational system. The flight duty cycle involves many takeoff and landing maneuvers with short cruise mission legs. Thus, the propulsion components are subject to a large number of cycles. This high cyclic requirement is partially offset by a lower design life requirement. For these design studies, in conjunction with NASA, the duty cycle and life requirements of the turbotip fan for the RTA were defined. Figure 1 gives the research duty cycle which consists of one cruise mission, three short takeoff (STOL) circuits, and three vertical takeoff (VTOL) circuits per hour of operation.

Conversion of these duty cycles to the normal parameters required for propulsion design produced the breakdown as shown in the following table:

Cycle Comparison

Percent of Life	ASW	RTA
VTO	0.7	10.0
Intermediate	5.0	13.3
75% to Inter	11.0	70.0
Less than 75%	83.3	6.7
Cycles per Hour	0.6	12.0
Mission Severity	1.0	15 to 20

For comparison, a similar breakdown is given for a typical antisubmarine warfare (ASW) mission. Comparison of the mission shows that the research duty cycle is about 15 to 20 times more severe than an operational mission.

For the 10 percent of operating time spent during takeoff and landing, the propulsion components will be subjected to rapid cyclic variations associated with thrust modulation for aircraft attitude control. For these studies, the thrust changes for control were selected to be 20 percent of the fan nominal lift during takeoff. This level of control power is consistent with the results of numerous aircraft system studies. The duration and frequency of these control excursions, to be used in the design of propulsion for the RTA, are as shown in Figure 2.

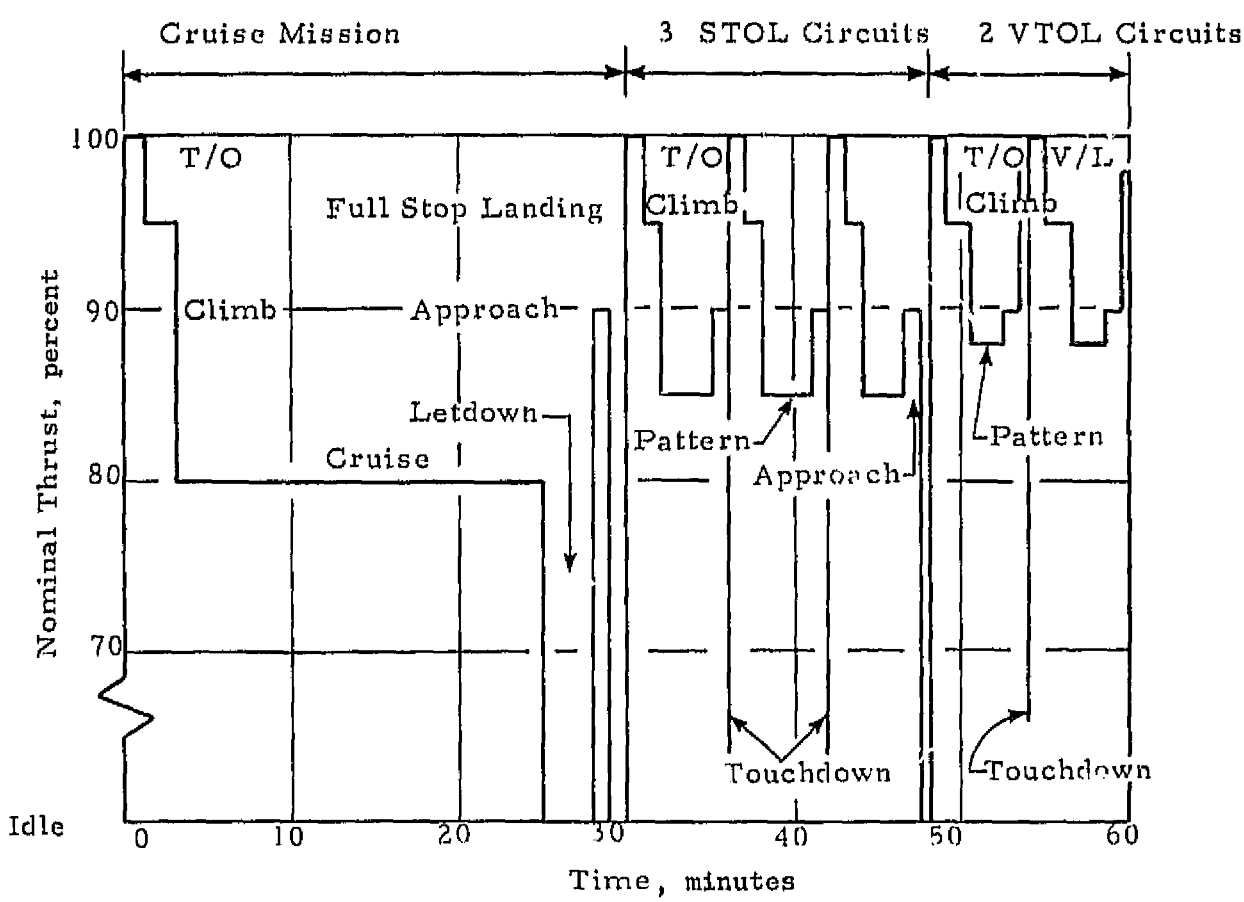


Figure 1. RTA Mission Duty Cycle.

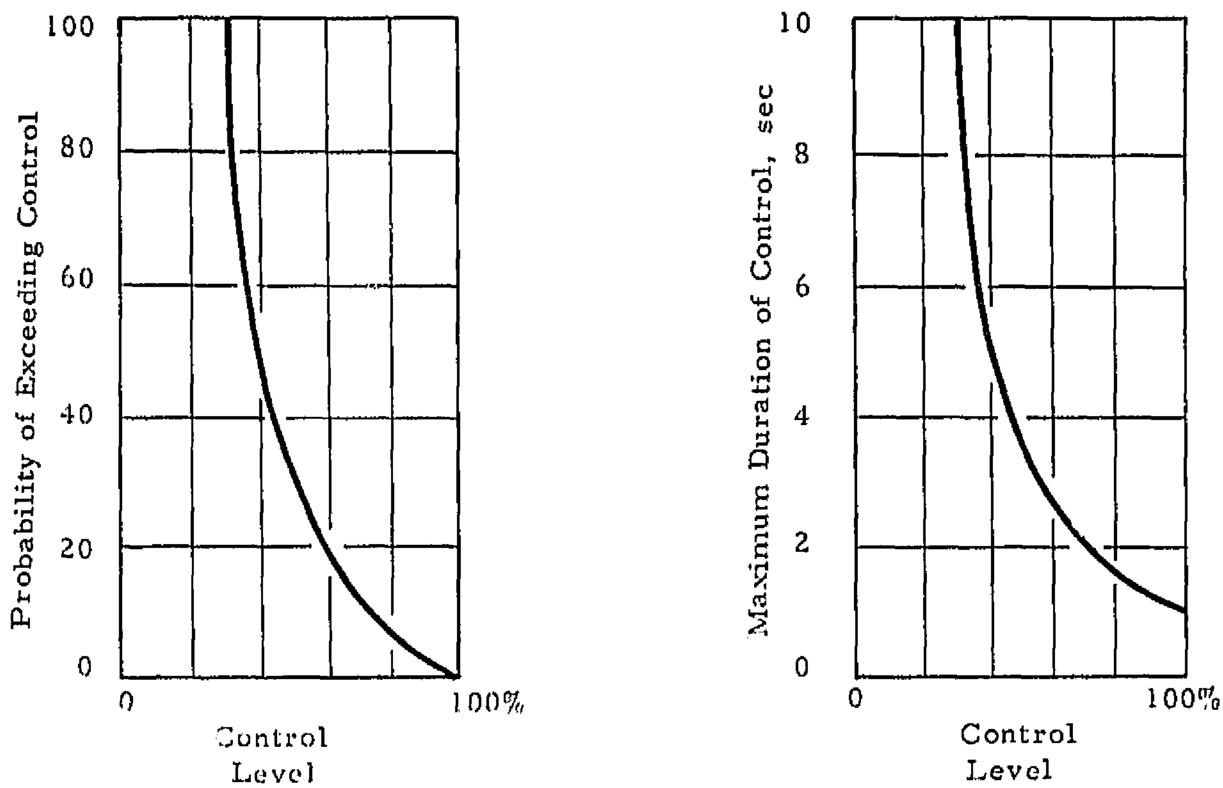


Figure 2. Control Duty Cycle.

3.2 Design Life

Design life of the propulsion system has a significant effect on system weight and cost. For the research type mission, the percent of exposure time to high power levels and the number of start-stop cycles are also relatively high. Combining these effects, the design life selected for these design studies was as follows:

- hot parts.....600 hours.
- cold parts...1200 hours.

Based on the RTA duty cycle, the time in VTO mode was set at 10 percent of the design life and the number of start-stop cycles shall be at least 12 per hour of life.

3.3 Design Requirements

The design requirements established for the design studies were based on the requirements of Reference 2, with modifications. The significant changes to the specifications include the following:

- Bird ingestion limited to one 2.2 pound bird with some minor fan damage.
- Reduced minimum loads of 2.0 radians per second maximum.
- No provision for fan blade containment.
- Reduction of sand ingestion requirements to two hours.

In addition to the military standard requirements, certain desirable design features or requirements were also established, such as:

- On-wing fan blade, rotor disk, and sump removal.
- Integral fan lubrication system, separate from the engine.
- Provisions for aircraft accessory power takeoff from the fan shaft.

3.4 Gas Generator

The YJ97-GE-100 gas generator was selected for the RTA system based on engine availability, low cost for refurbishment of the engine, and the good match of available gas horsepower. As established in the RTA requirements, the aircraft shall be capable of a vertical landing following failure of one of the gas generators. This requirement necessitates the use of three gas generators for the system.

The propulsion package for the RTA thus consists of three gas-coupled LCF459 fans and three YJ97-GE-100 engines.

4.0 TURBOTIP FAN DESCRIPTION

The LCF459 is a high bypass fan system gas-coupled to a remote gas source or engine. Figure 3 shows a sketch of the LCF459 as the design existed at the initiation of these cost reduction studies. Details of the design are given in References 1 and 3. The major fan components are identified, such as the scroll, rear frame, fan rotor, tip turbine, and bearing system. The fan system is designed to be self-sufficient, without using any gas generator systems for lubrication or cooling.

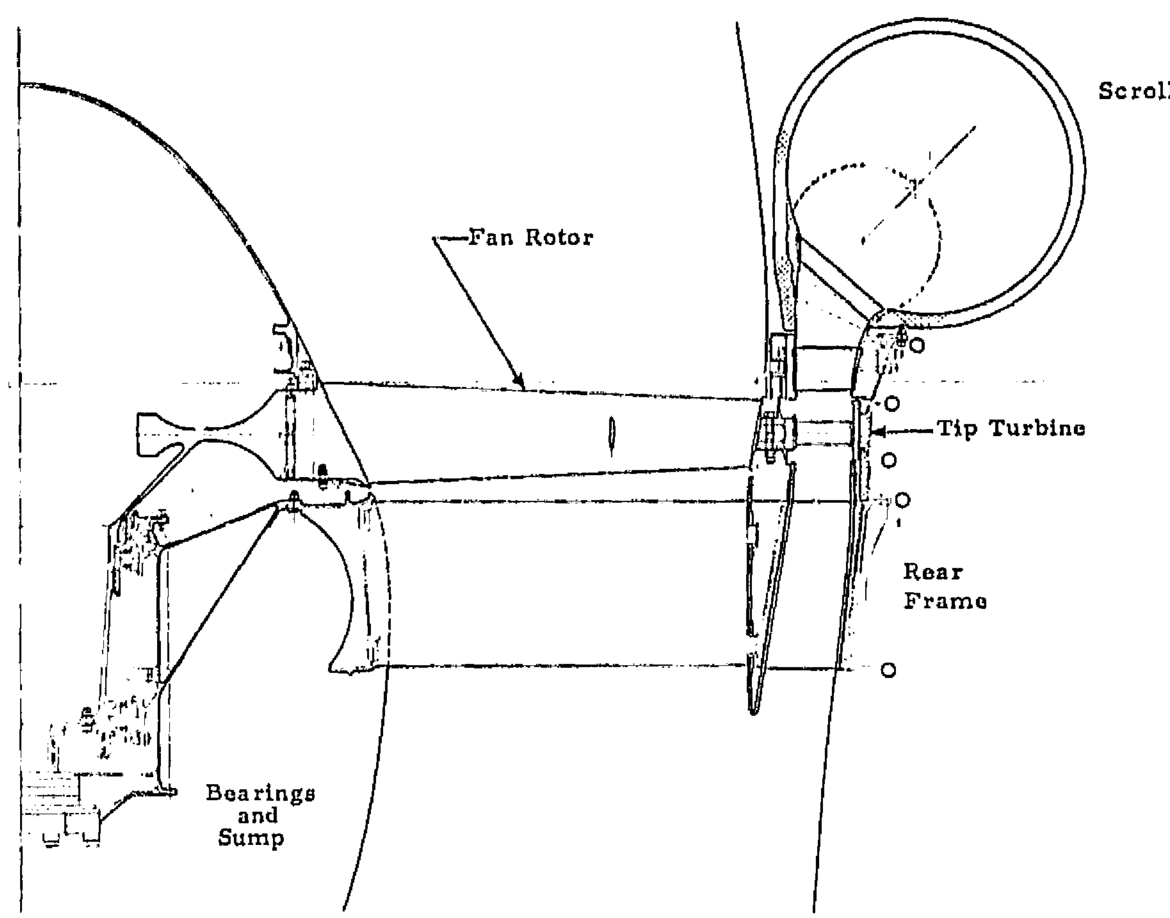


Figure 3. LCF459 Fan at Conclusion of Preliminary Design Studies.

5.0 COST REDUCTION STUDIES

The primary objective of the studies was to reduce the manufacturing costs of the LCF459 turbotip fan system. The approach was to concentrate on those areas where design and/or material changes would produce significant savings. The objectives were to reduce the manufacturing costs per unit by 20 percent. The areas given particular attention included:

- Scroll design and material.
- Rotor blade material.
- Method of rotor blade to turbine carrier attachment.
- Rear frame material.
- Lubrication system and sumps.

The following discussion describes the design features considered and the results of these cost reduction studies.

5.1 Scroll

The scroll of a turbotip fan is normally the highest value component of the fan assembly, representing about one-third of the total cost. Cost reduction studies of this component were directed at four areas of the design:

- Material changes, particularly from René 41 to HS188 for the major scroll structure.
- Elimination of the inner-outer scroll configuration.
- Simplification of scroll mounting.
- Simplification of scroll structure around the inlet duct.

The reference LCF459 scroll as defined at the conclusion of the preliminary design studies incorporated an inner and outer scroll arrangement. A sketch of this arrangement is shown in Figure 4. The requirement for the double scroll arrangement is brought about by the scroll operating areas required for a two engine, three fan arrangement. Operational V/STOL systems, as proposed by the airframers, use two engines divided among three fans in the takeoff mode. Thus the scroll for each fan is fed through the 240° outer scroll with the 120° segment closed by a valve located at the inlet to the inner scroll, Figure 4. If a single wall scroll configuration were used, the inactive arc would have a low duct metal or skin temperature while the active arc would be at engine exhaust gas temperature. This large temperature difference, active versus inactive arcs, would

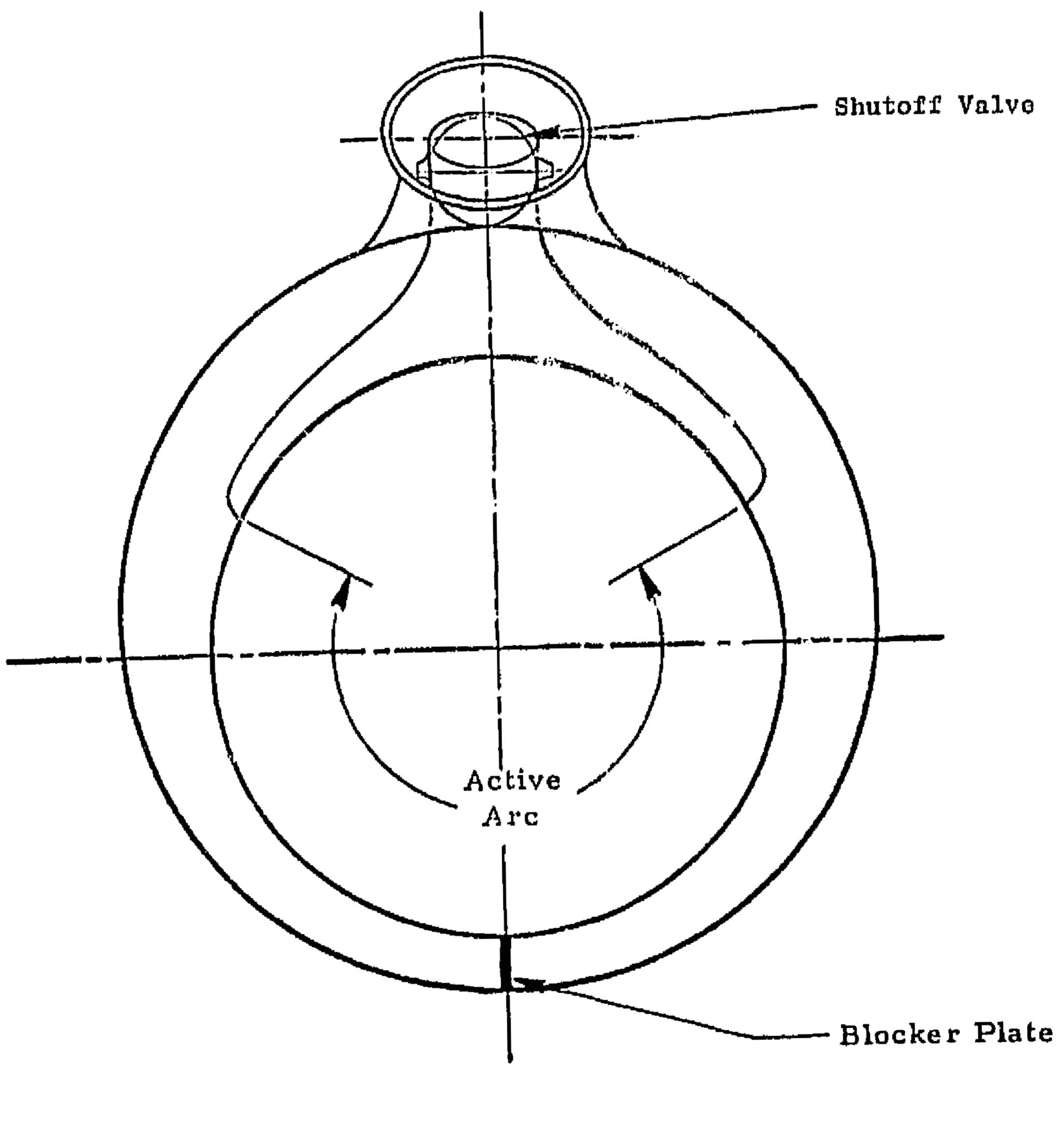


Figure 4. Scroll, Double-Wall Design Shutoff Valve.

produce intolerable thermal stress and distortion of the scroll structure. The double scroll, inner and outer, is the method selected to yield more uniform temperatures and thus acceptable stresses and distortion. This double wall configuration represented a relatively expensive but desirable arrangement.

For systems operating at the takeoff condition in an RTA, three gas generators will be used to drive three fans and the scroll will be uniformly heated. The temperature difference due to partial arc operation, and the requirement for a double wall scroll no longer exist. However, partial arc operation is still required during one engine inoperative (OEI) conditions, and scroll shutoff is accomplished using a valve in one arm of the scroll, Figure 5. This method of partial arc operation; for an RTA, is acceptable for the following reasons:

- OEI conditions will exist only after the fan has been operating for some time at the full-arc, all engine operating condition. The full scroll structure would be uniformly heated.

- Operation in the OEI condition will occur for only about 30 seconds, during which time the inactive arc structure will not cool down significantly.

- OEI conditions are not a normal, every flight occurrence. OEI operation will probably be investigated during RTA flight testing that will represent only about 5 to 10 percent of the total fan operating time.

A significant scroll cost reduction was achieved by elimination of the double wall construction. Another significant scroll cost reduction can be obtained through substitution of a less exotic material in place of the René 41. First, the temperature levels will be lower for the YJ97-GE-100 engine as compared to growth J97 or advanced cycle engines. Secondly, the engines will operate at lower power settings since a three engine-LCF459 configuration will have a maximum thrust capability of about 146.8 kN (33,000 pounds) as compared to an aircraft thrust requirement of about 124.6 kN (28,000 pounds). At this reduced thrust setting, the scroll temperature will be significantly lower.

The two less exotic materials considered for fabrication of the scroll were Hastelloy X and HS188. Both of these materials have been used for the fabrication of scrolls, ducting, and diverter valves of previous turbotip systems. The HS188 material was selected for the scroll design because of its higher rupture strength and ductility along with relative ease of manufacture and field weld repair. Figure 6 compares the material properties of Hastelloy X and HS188. The one disadvantage of the HS188 is its 10% greater density due to a cobalt base of HS188 versus nickel base of Hastelloy X.

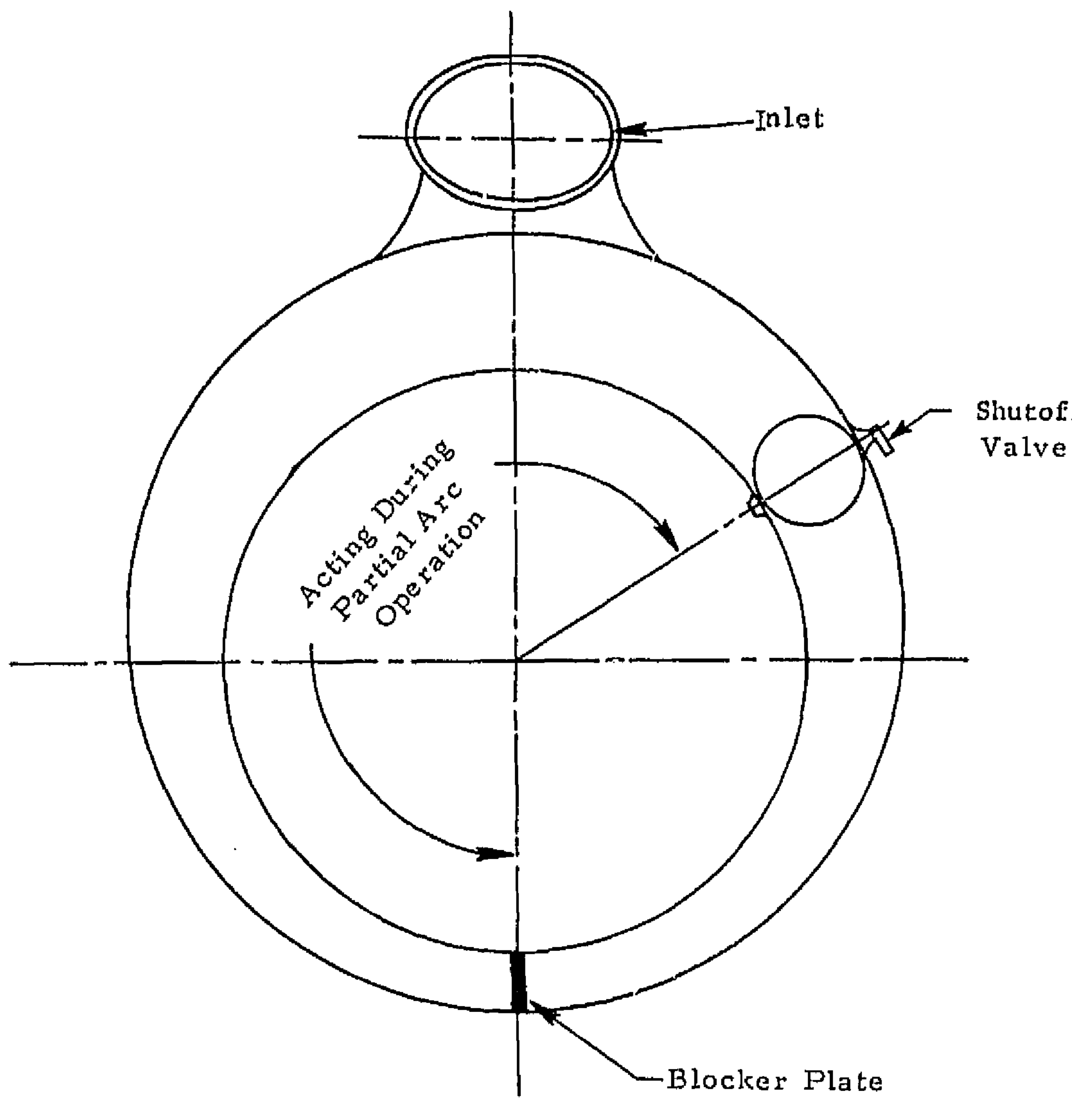


Figure 5. Scroll, Single-Wall Design.

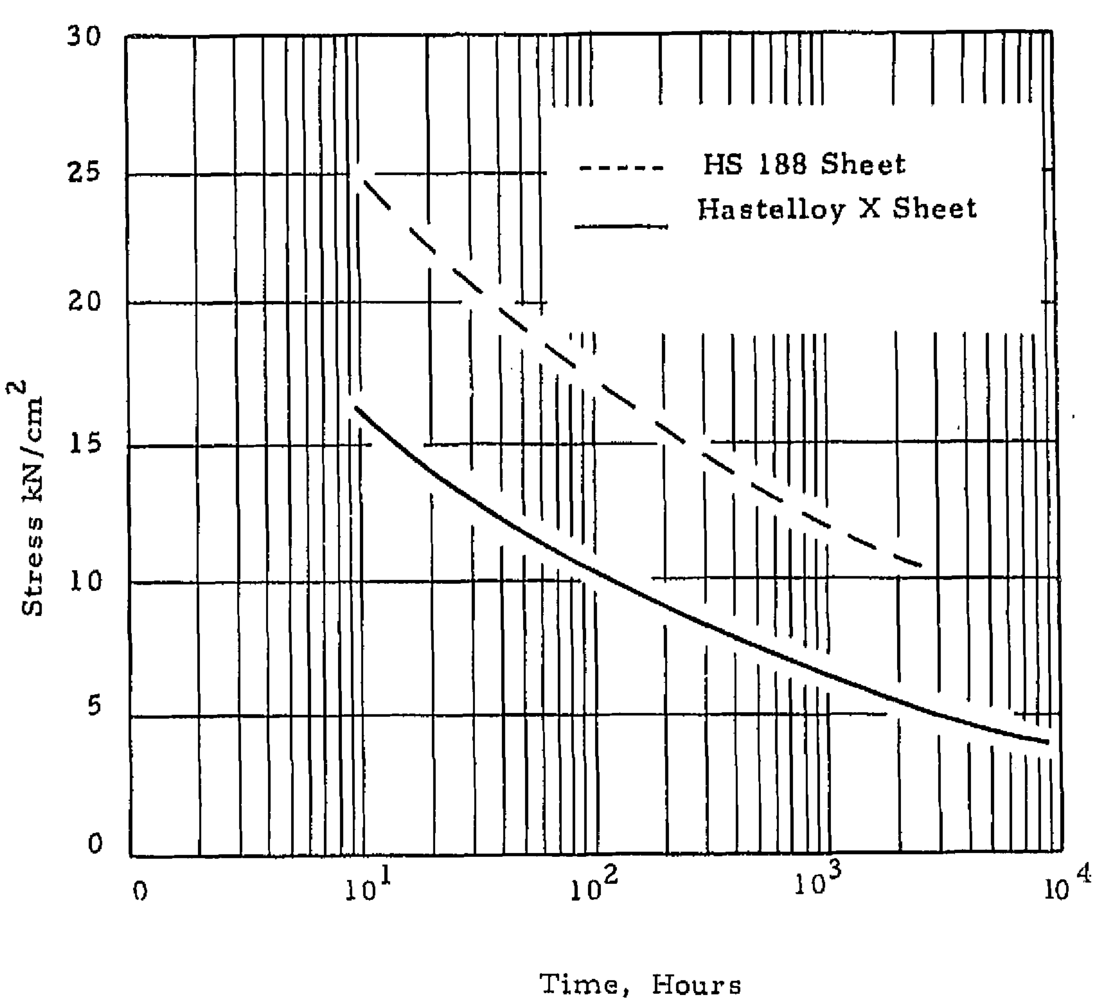


Figure 6. Comparison of Hastelloy X and HS188 Material Properties at 760° C (1400° F).

One other feature that has been incorporated in the LCF459 operational design was an elliptical flange which permitted removal and replacement of the scroll inlet sections to match multiple, lift/cruise and nose fan installations. This arrangement was used to provide commonality in the design and thus ease the fan logistics problem.

For a research fan system, logistics is not as great a problem. A study was undertaken to determine the relative cost of keeping the elliptical flange design versus making two different scrolls for the particular installations. The latter case, two scrolls, represented a lower overall cost than the elliptical flange design.

Other minor design changes in the scroll included the method of scroll mounting and sealing. The original design used an axial load stop and 18 tangential load pins for scroll mounting, Figure 7. In the revised design, the scroll is mounted at three equally spaced locations. Links are used to attach the scroll to the fan case. Replacement of the pins with links reduces the possibility of binding and excessive friction during thermal growth of the scroll. Figure 7 compares the cross sections of the preliminary and present scroll designs.

Manufacturing cost estimates were made for the two scroll designs. A comparison of scroll unit price shows a cost reduction of 17 percent over the original design.

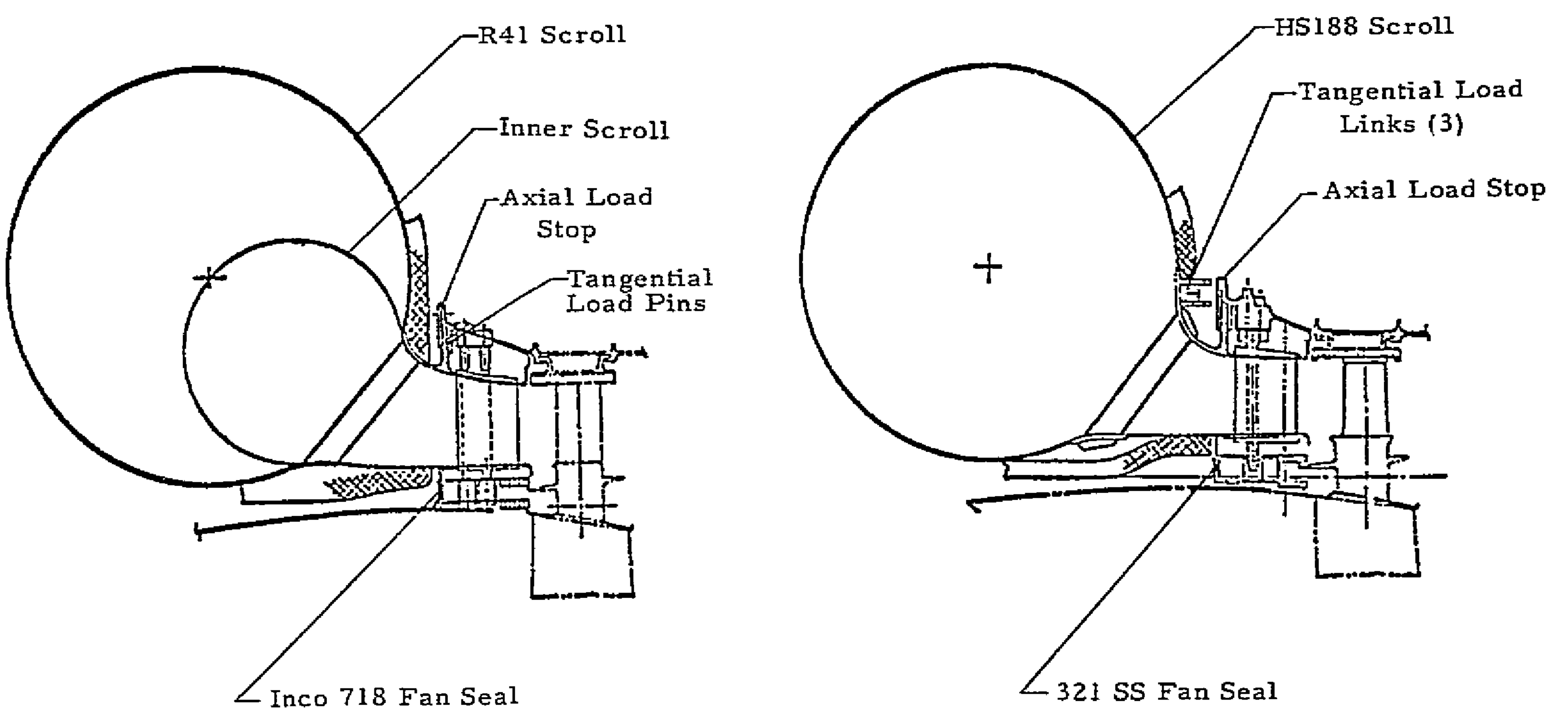
The net result of the design studies produced a slight increase in scroll weight from 111.1 kg (245 pounds) for the preliminary design to 116.1 kg (256 pounds) for this low cost design.

5.2 Rotor

The rotor of a turbotip fan includes the fan blades, the tip turbine, the rotor disk and stub shaft. Cost reduction studies for these components included the following:

- Fan blade material substitution for the proposed Ti 17 material.
- Methods of fan blade to turbine tip tang attachment and tang cooling.
- Simplification of disk-stub shaft design.

The fan blade design selected at the conclusion of the preliminary design used Ti 17 material. This titanium alloy is a high strength, high temperature material presently used for manufacture of rotor disks. The LCF459 is a new application for this fan blade material. The use of this material represented a significantly higher cost for blade forgings as compared to the more conventional titanium alloys.



Preliminary Design

Present Design

Figure 7. Scroll Comparison.

A study was performed to evaluate the effects of substituting a more conventional Ti 6-4 material for the blades. A comparison of the material properties, Figure 8, shows the higher strength of Ti 17 on both a strength basis and fatigue capability. For the LCF459 blade design, the Ti 6-4 material exhibits adequate material properties providing the tang temperature remains below 316° C (600° F). The low cycle fatigue (LCF) life at this condition is 56,000 cycles. For the RTA duty cycles with 12 start-stop cycles per hour for 1200 hours, the cyclic exposure will be 14,400 in the life of the component. The 56,000 cycle capability is adequate to meet the design standard of having an LCF life equal to at least twice the expected cyclic exposure.

Tang attachment and cooling studies were also conducted as part of this activity. The results of these studies are presented in the following discussion.

Previous turbotip fan designs, as well as the preliminary LCF459 design, used a single through-bolt for attachment of the turbine carrier to the fan blade tip. This method of attachment required both bolt shear and clamping force to resist the carrier centrifugal loads. Without bolt preload or clamping action, the tang and bolt have adequate strength but the LCF capability is significantly lower.

For example, the baseline LCF459 design used an 11-mm (7/16-inch) bolt of a high strength (MP519) material. This configuration gave the following LCF capabilities at 316° C (600° F).

- With preload - 49000 cycles
- Without preload - 9300 cycles

It is apparent that this design did not have adequate LCF for the possible case where the tang bolts were not properly torqued. Use of larger bolts would make the tang geometry too large for an attractive design.

A new superior tang attachment was defined during these studies. This configuration employs both a tang bolt and a rabbet surface at the end of the blade tang. A comparison of the original and modified tang attachments is shown in Figure 9.

The use of a rabbet attachment permits use of a smaller bolt, 8-mm (5/16-inch), which does not rely on preload for load carrying. Even without preload, the LCF life is 47,000 cycles, which is more than adequate to meet the LCF design objectives.

All of the previous designs were postulated with the assumption that the blade temperature at the blade attachment is 316° C (600° F) or less. A design study was conducted to define a tang cooling system that scrubbed the sidewalls of the carrier with cool air. A second feature also considered in the design

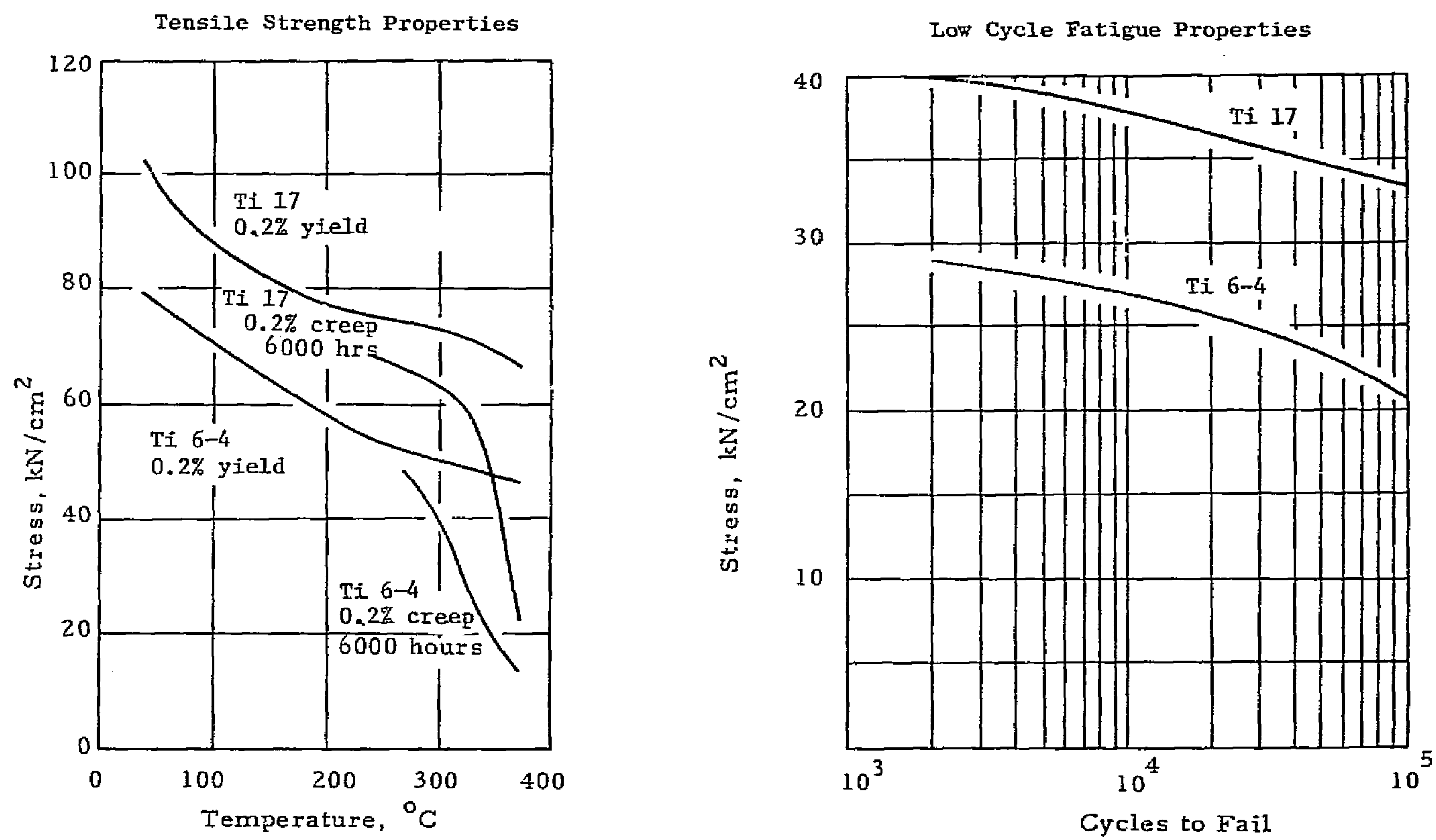
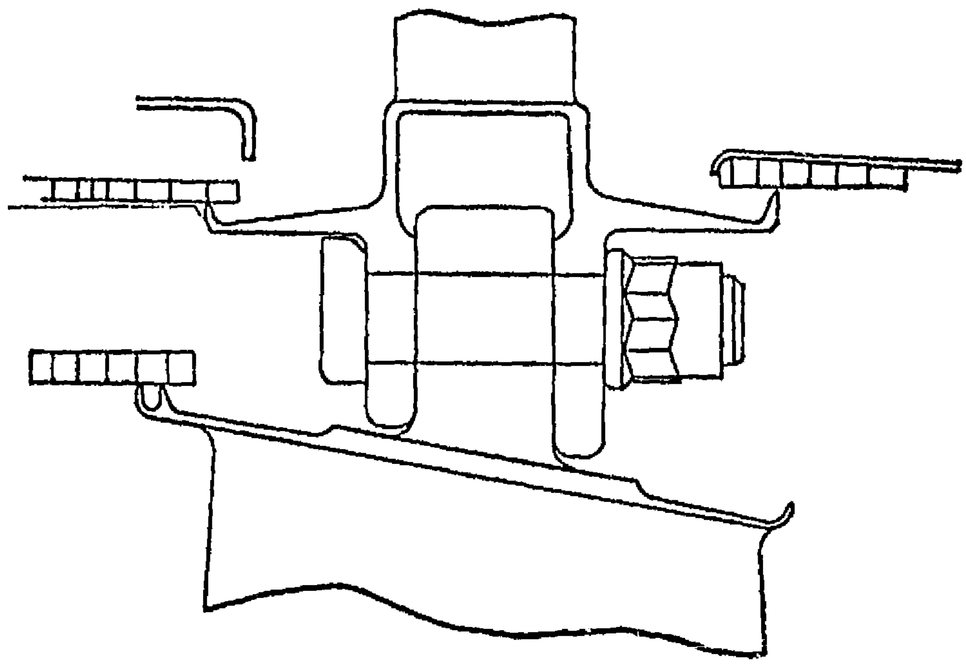


Figure 8. Titanium Properties Comparison.

• Bolt



• Rabbet and Bolt

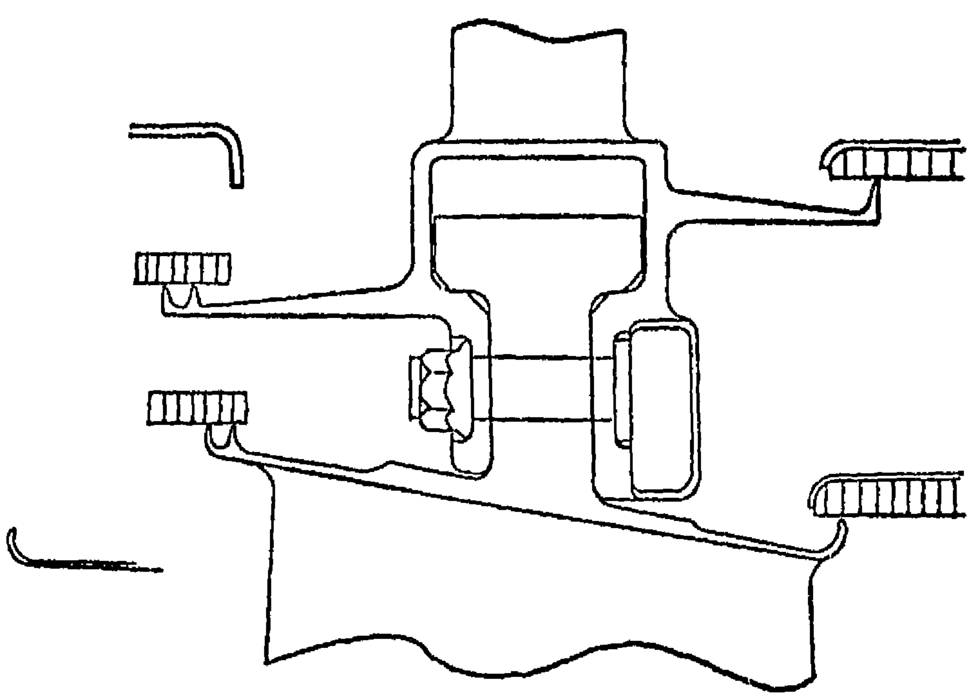


Figure 9. Fan Blade-Tip Turbine Attachments.

was the capability to pump cooling air into the forward seal cavity to reduce hot gas leakage into the fan rotor inlet. This cooling scheme is shown schematically in Figure 10. The carrier assembly is shown schematically in Figure 11.

This cooling system picks up air at the fan discharge through scoops on the fan flowpath liners. The air flows through the mid-box cavity and is recovered by scoops fabricated in the rear side of the carriers. Each of the 52 carriers has one scoop. Because of the tangential velocity due to rotational speed, the air is pressurized and then flows through a passage in the carrier to the forward air seal pocket. Through proper sizing of the scoop areas, the pressure in the cavity is assured to be adequate for flow to pass from the seal cavity into both the turbine and fan flow paths. An estimate of design point air flow rates is shown by Figure 10. For the final design of the cooling system, more detailed calculations involving clearance variation with speed and temperature must be completed. The initial analysis does show that the cooling system is adequate to ensure cool air scrubbing on both sides of the carrier. Initial estimates indicate that the tang temperature will be below 316° C (600° F) as required for the application of Ti 6-4 as the blade material.

Another minor modification of the reduced cost rotor design occurs in the disk stub shaft. In the preliminary LCF459 design, the stub shaft was inertia welded directly to the fan disk as a weight reduction technique. A bolted flange is just as adequate and represents a lower cost design for the small number of units required for a research program. Figure 12 compares the bolted design with the original inertia welded disk-shaft.

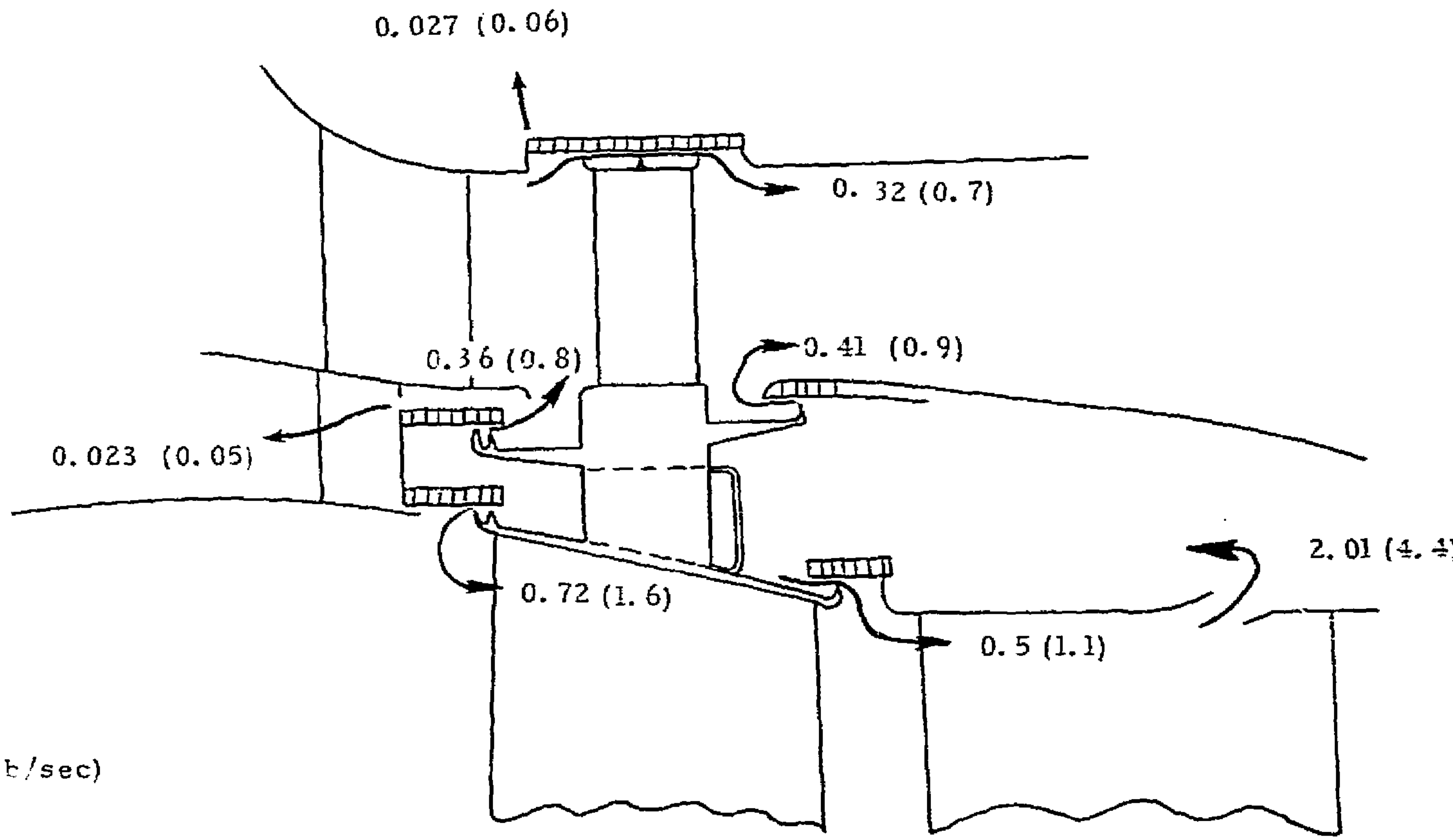
The net result of the design studies in the rotor area produced a 10 percent cost reduction, primarily due to substitution of Ti 6-4 for the Ti 17 blade material. There was no significant change of the rotor weight.

5.3 Rear Frame

The design studies of the rear frame, directed towards cost reductions, centered around two areas.

- Material substitutions
- Fabrication methods

The rear frame is a fabricated component. Material fabrication properties and raw material costs have a significant impact on the total part cost. The preliminary design frame of the LCF459 was fabricated mainly of Inco 718 material. This material is a high strength, high temperature nickel base sheet, bar, and cast material. A lower temperature iron base material, 17-4PH, was studied for application in a reduced cost frame design. The major difference in material properties occurs in the maximum temperature capability, 316° C (600° F) for 17-4PH versus 649° C (1200° F) for Inco 718.



Units
kg/sec (lb/sec)

Figure 10. Carrier Cooling - Air Pump System.

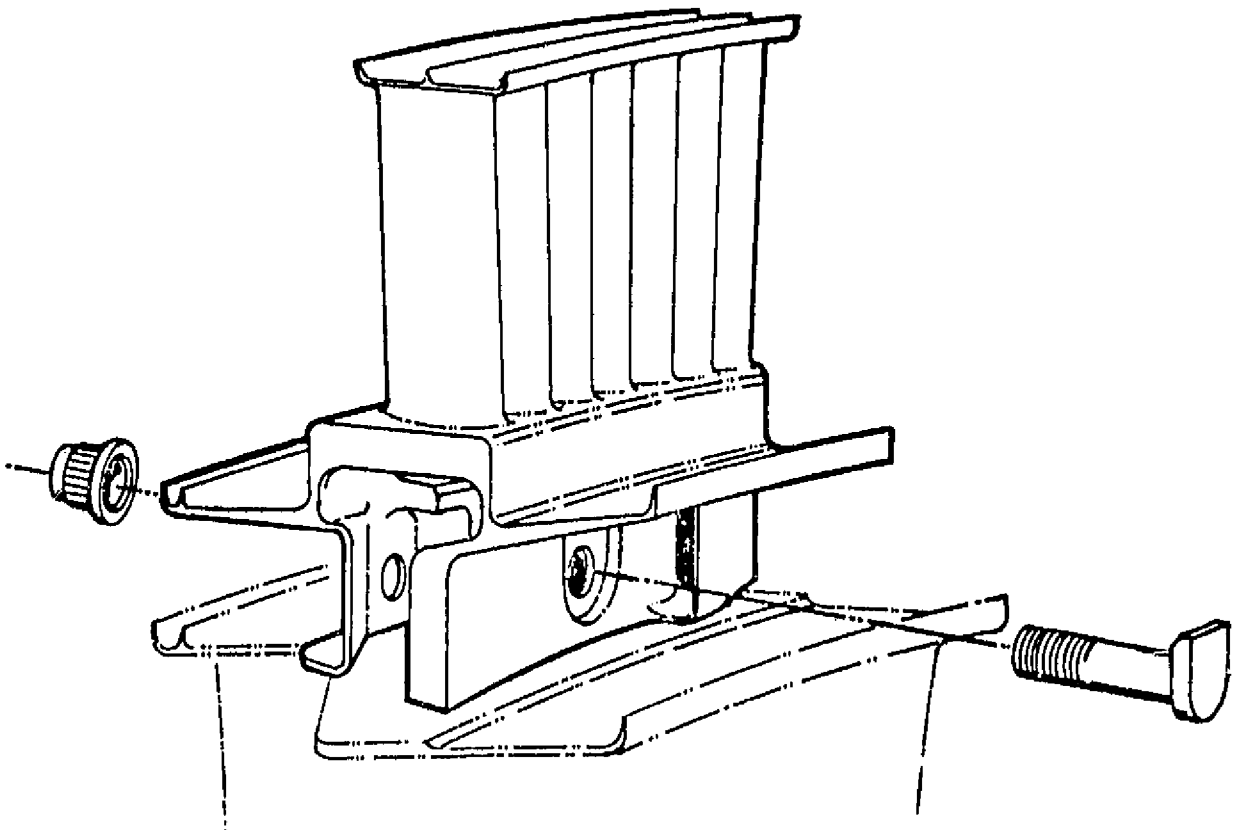


Figure 11. Carrier Assembly.

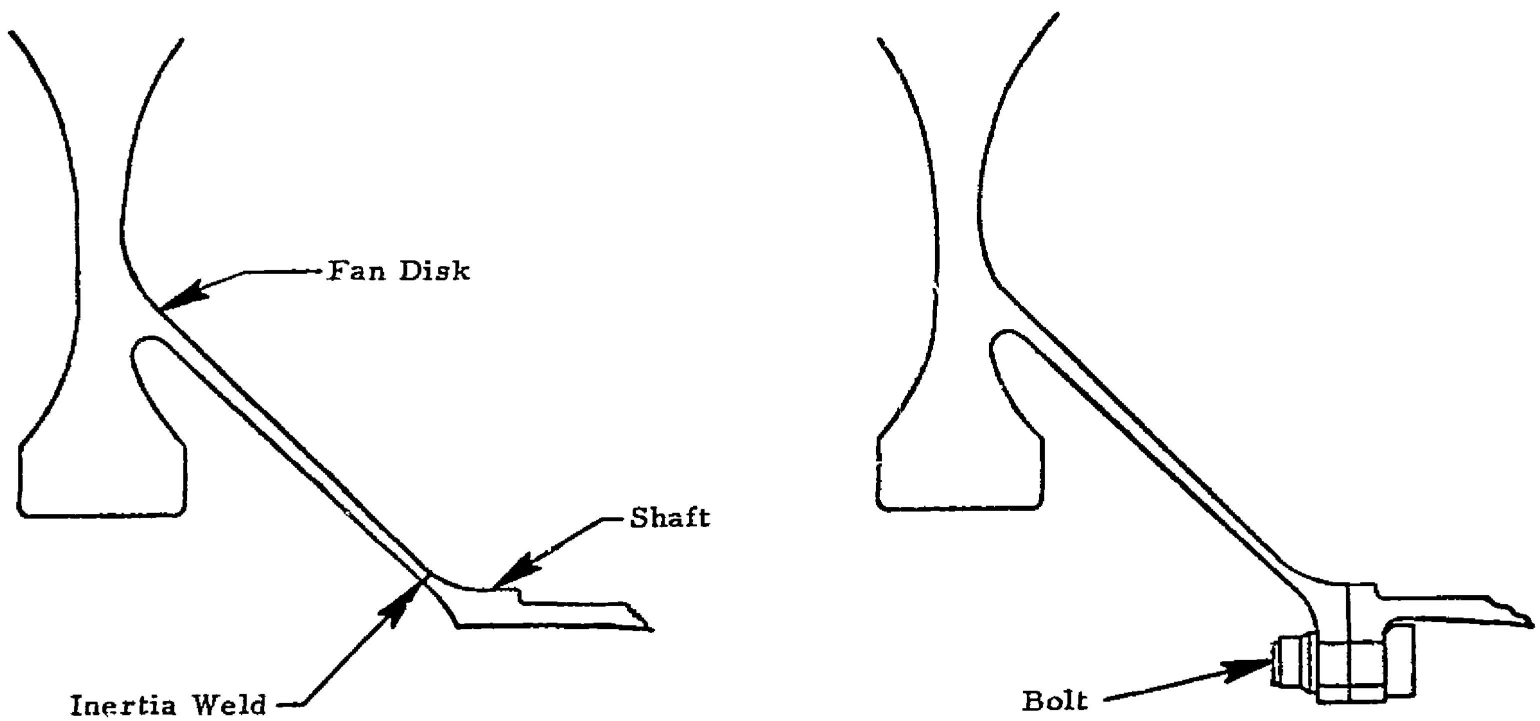


Figure 12. Disk Shaft Attachment Comparison.

The major portion of the fan frame is subjected to the cold flow environment of the fan exhaust stream. The only hot sections are the outer 10 cm (4 inch) of the annulus. The full outer case of the frame will be cooled to a maximum of 232° C (450° F) to maintain low thermal stresses and acceptable seal clearances between the case and the fan and turbine tips. Substitution of the 17-4PH material would require only a minor amount of additional structural cooling where the struts pass through the hot turbine exhaust, and therefore is a reasonable material change.

Three methods of cooling the struts were considered: film, convection, and impingement. The flow rates required for these three cooling methods are as follows:

Cooling	Flow (kg/sec)	Flow (lb/sec)
Film	0.56	1.23
Convection	0.45	1.00
Impingement	0.43	0.94

The impingement cooling system was selected based on the least risk, lowest cost, and lower flow requirements.

Another fairly sizeable cost reduction was accomplished by changing the type of panels that separate the fan and turbine flowpaths, as shown in Figure 3. The original preliminary design used fabricated honeycomb panels of Hastelloy X material. The revised design uses chem-milled waffle type panels of the same material. The major cost reductions occur because of the change in fabrication methods. Figure 13 shows a comparison of the frame outer structure for the original preliminary and present designs.

The results of the frame cost reductions, material substitution, and fabrication methods gave an estimated development manufacturing cost 24 percent lower than the original design. A weight increase occurred, with a new frame weight of 122 kg (270 pounds) compared to the original of 107 kg (235 pounds).

5.4 Bearings and Sump

The design requirement has been established that each remote fan system shall have its own integral lubrication system. At the conclusion of the preliminary design, the bearing and lubrication system was as shown in Figure 14. The configuration contained a fan driver lubrication-scavenge pump, with remotely located oil tank and heat exchanger. Both the oil tank and heat exchanger would be aircraft-furnished components in this configuration.

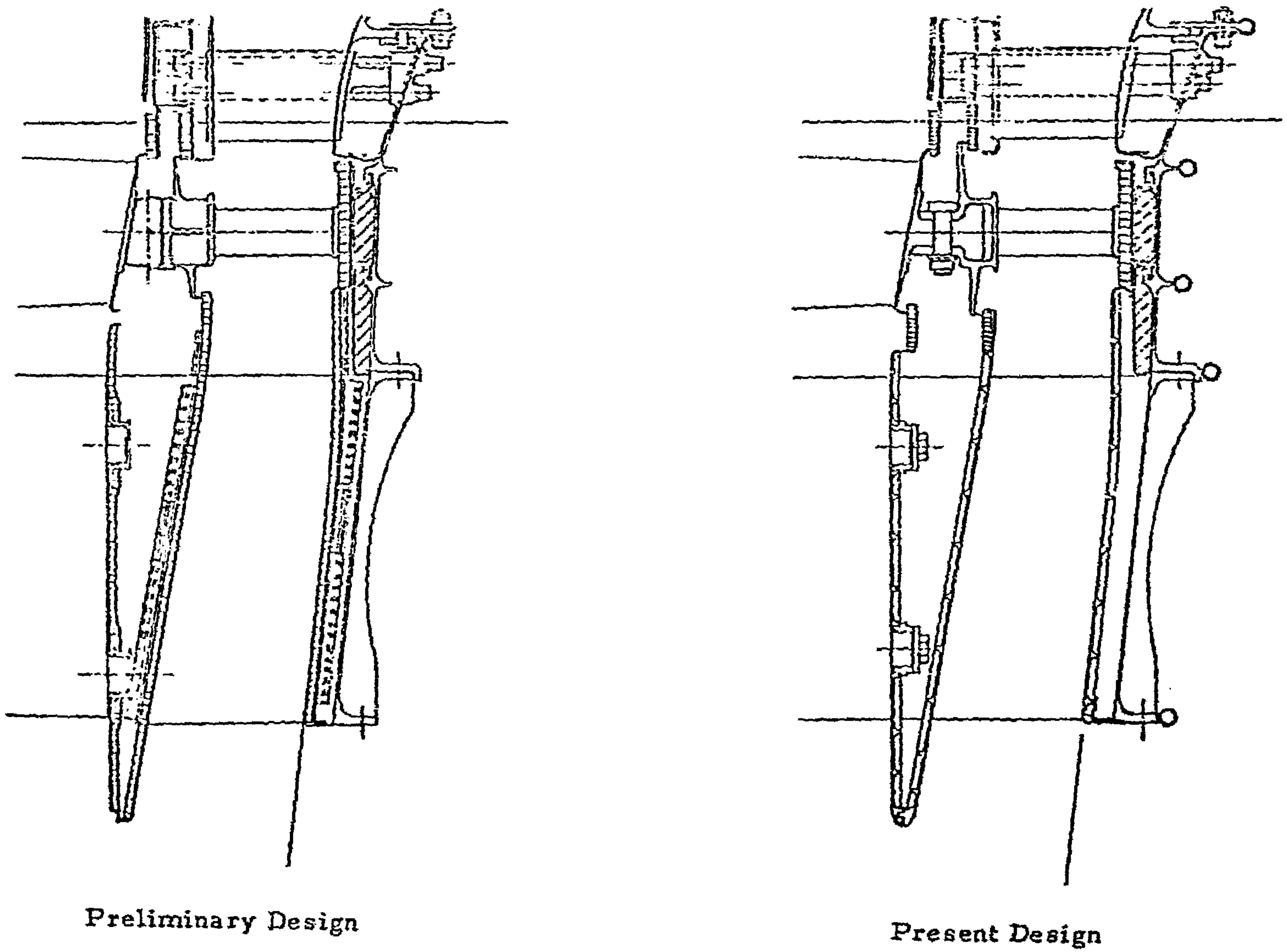


Figure 13. Frame Outer Flowpath Comparison.

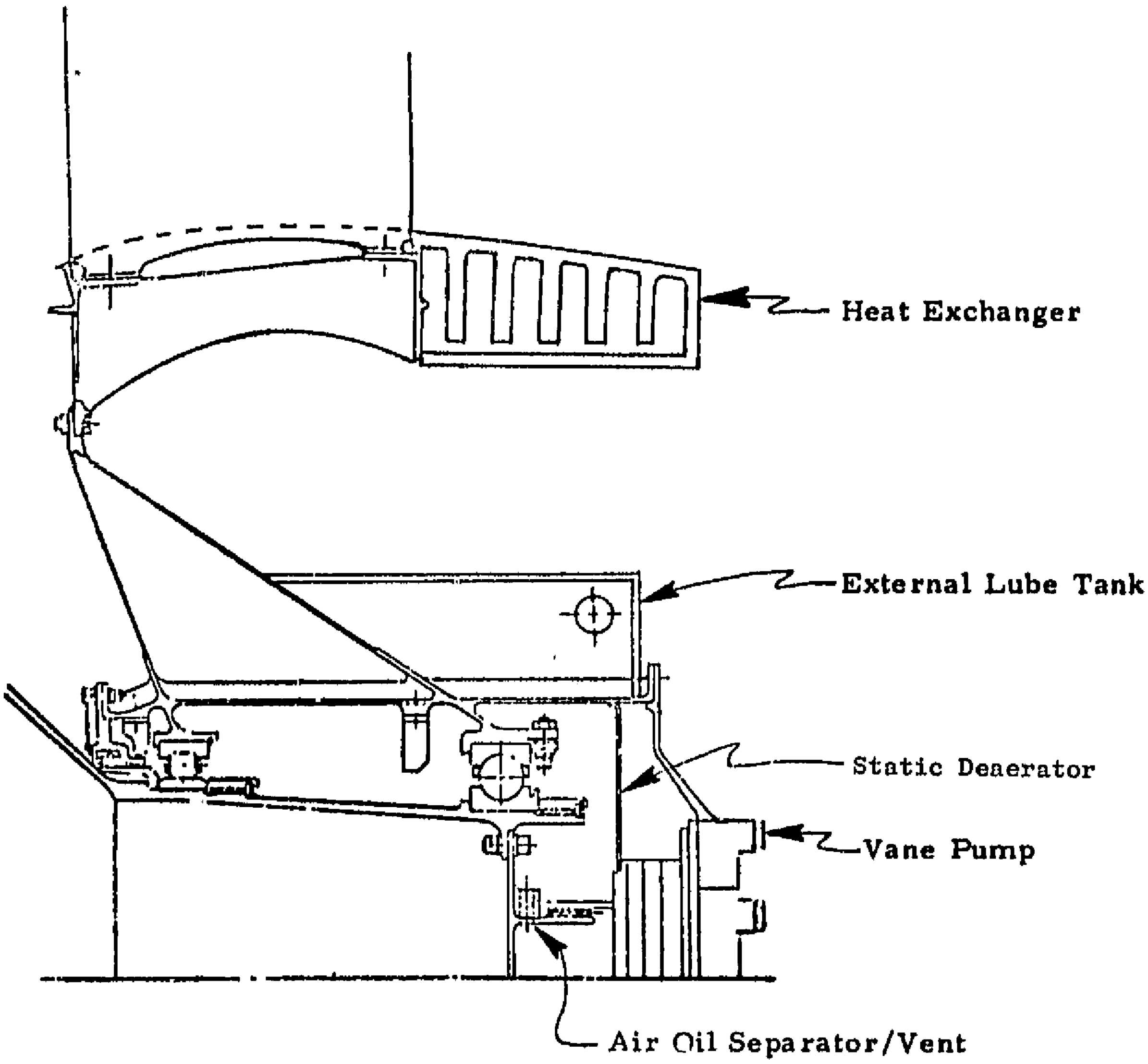


Figure 14. Preliminary Design Sump.

As part of these design activities, studies were conducted to define a more simplified and reliable method of lubricating the fan bearings. These studies defined the configuration as shown in Figure 15. The unique feature of this design is the use of viscous pumps for supplying oil to the bearings.

The configuration uses two rotating disks or pumps mounted on the rotor shaft to pump oil into a collector tube. This collector passage directs the oil flow into an air-to-oil heat exchanger. The outlet of the heat exchanger then feeds oil through a jet into a pocket in the rotating shaft. Orifices in the rotating shaft meter the oil to the bearing inner race. Bearing under-race lubrication is thus provided. The discharge oil is collected in the reservoir, which is an integral part of the bearing housing. The disk pump picks up the oil from this reservoir to close the cycle. A rotating air-oil separator is located in the forward part of the bearing housing and disk support cone. Oil cooling is provided for discharge air which is used to ventilate the cavity around the reservoir and heat exchanger.

The new sump and lubrication system represent a more reliable design over the initial system. A highly reliable viscous pump, similar to a proven design used on the CF6 engine, replaces the normal lubrication and scavenge pumps. The complete reservoir and heat exchanger system is integral with the bearing housing and provides a small compact system. The impact of this new design has only a minor effect on fan cost and weight, but provides a much more reliable and simplified system.

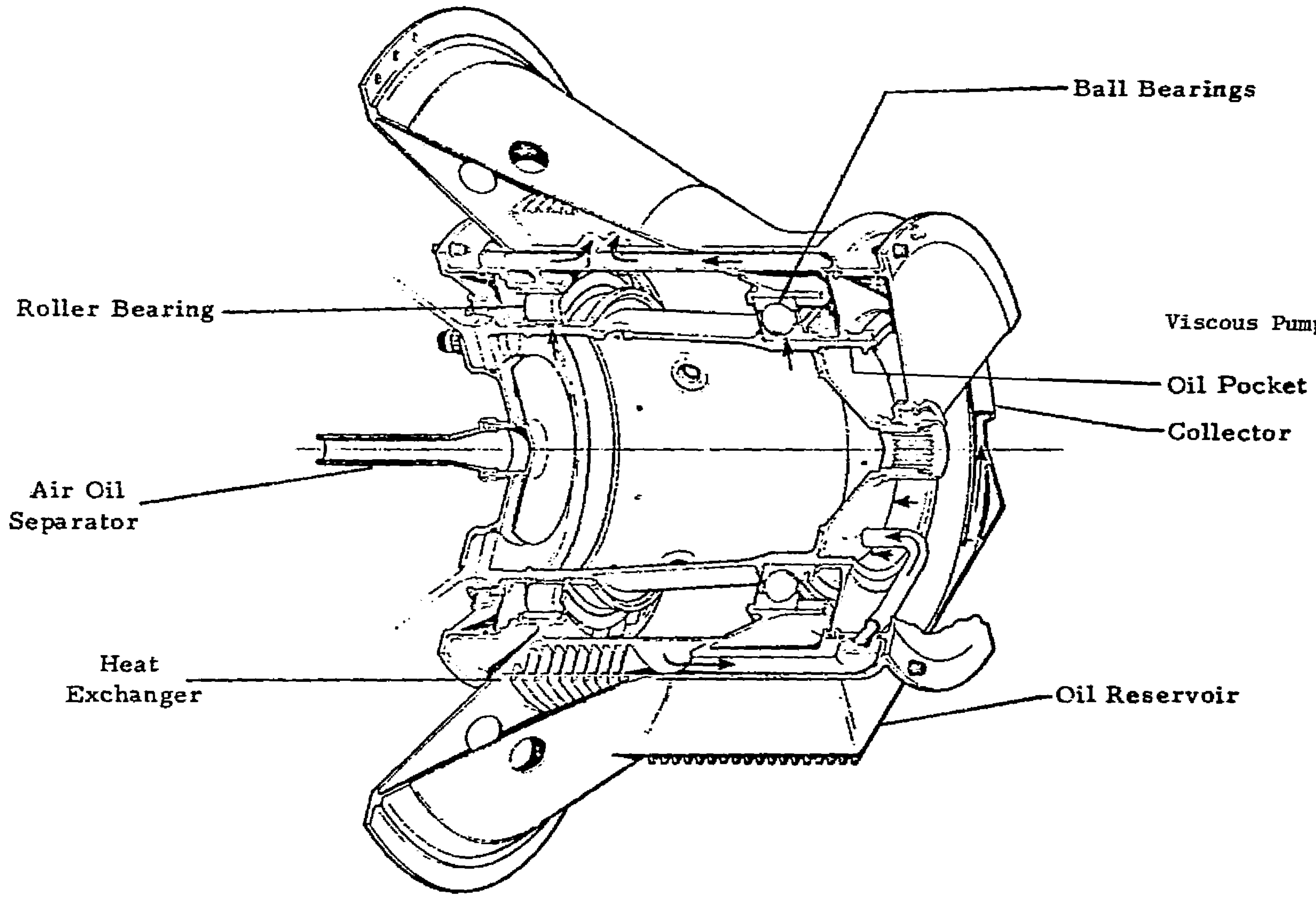


Figure 15. Revised Design Sump.

6.0 CONCLUSIONS

Trade studies were performed to define design changes on the LCF459 which represent a significant reduction of fan unit manufacturing cost. Some of the design changes were possible because in the RTA system, the fan is restricted to operation with the YJ97-GE-100 in a three fan-three engine arrangement. The major design changes selected for carry-over into the detail design phase are:

- Ti 6-4 material for fan blades.
- Turbine carrier with rabbet attachment and cooling scoops.
- HS188 material for scroll.
- Single bubble scroll mounted to the frame using links.
- 17-4PH material fan frame with simplified flowpath liners.
- Integral lubrication system using viscous pumps.

The effect of these design changes is an overall 14 percent reduction in fan unit manufacturing costs. The breakdown of the cost reductions for each fan major component is as follows:

Component	Cost (pct of fan assembly)	Cost Reduction (percent)
Scroll	32.0	17
Frame	20.6	24
Rotor	31.2	10
Sump	3.6	17
Minor Parts	12.6	0
Total	100.0	14

The design changes will also result in a lower risk, more highly reliable fan system for the RTA. At the expense of these changes, there is a slight increase in fan weight. The weight breakdown of the preliminary design configuration and the fan at the conclusion of these studies is as follows:

Component	PD Weight		Current Weight	
	(kg)	(lb)	(kg)	(lb)
Rotor	141	311	149	329
Bearings & Sump	27	59	28	62
Frame	107	235	123	270
Scroll	111	243	116	256
Total	386	850	416	917

7.0 REFERENCES

1. General Electric Company, Aircraft Engine Group, Cincinnati, Ohio: NASA/Navy Lift/Cruise Fan Preliminary Design Report, NASA Contract Report CR-134837, July 1975.

2. Military Specification: Engines, Aircraft, Turbojet and Turbofan, General Specifications for, MIL-E-5007D, October 1973.

3. General Electric Company, Aircraft Engine Group, Cincinnati, Ohio: Additional Design Studies of the NASA/Navy Lift/Cruise Fan, NASA Contractor Report CR-134928, January 1976.